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Catalytica ENERGY SYSTEMS

Fuel Processor Enabled NOx Adsorber After-Treatment System for Diesel Engine Emissions Control

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Outline

- Why use a fuel processor for NOx trap regeneration
- Overview of the fuel processor (XFP—Xonon Fuel Processor)
  - Application configuration
  - System efficiency
- Engine performance results
  - Fuel penalty
  - Low temperature operation
  - Operating range
  - NOx trap capacity
  - Desulfation of LNT
- Summary

Advantages of a Diesel Fuel Processor

What the fuel processor does

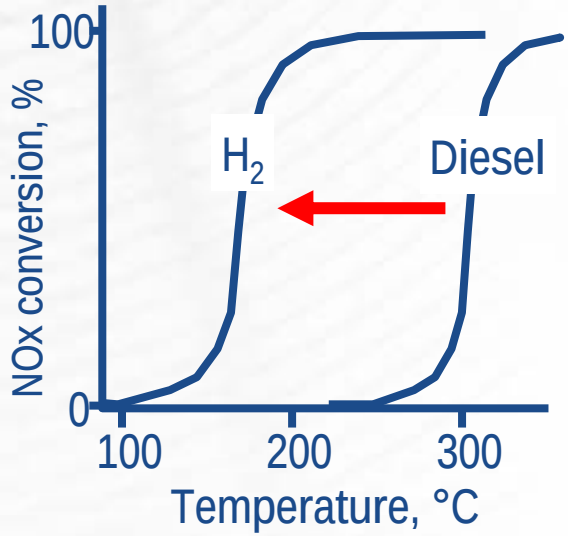
#1—Efficiently converts diesel fuel to REACTIVE REDUCTANTS

Benefits of Reactive Reductants

Regenerate the NOx trap at low temperatures
H_2 shown to regenerate NOx trap at 150°C

Reactive reductants used very efficiently by NOx trap

Complete regeneration of NOx trap capacity allowing minimum LNT volume



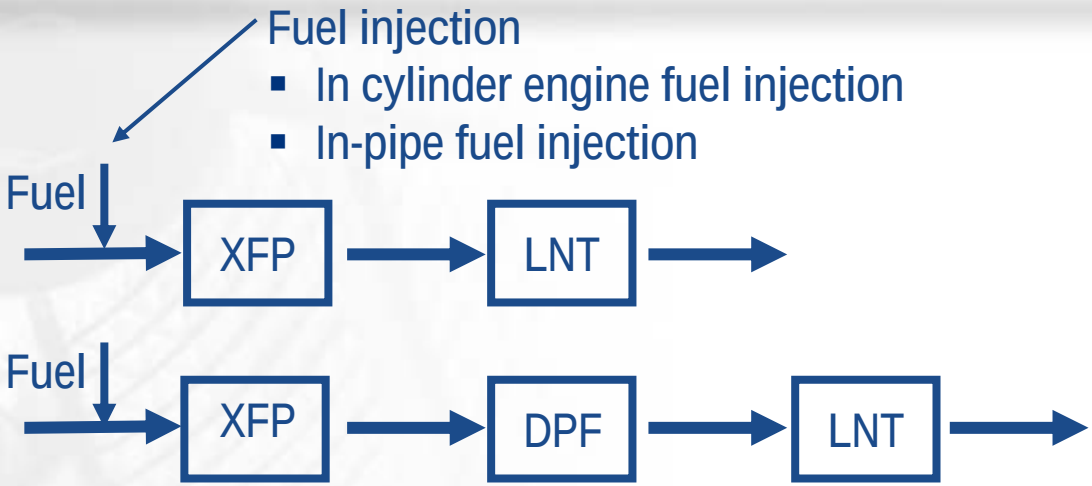
$2NO_2 + 4H_2 \rightarrow N_2 + 4H_2O$

Theoretical reductant Requirements

$$\frac{H_2 \text{ or } CO}{NOx} = 2$$

Large NOx trap capacity over wide temperature range

Application Configuration



- Separate components
- Components integrated into a single container

XFP Functions:

- Regenerate LNT
- LNT heat up and desulfation

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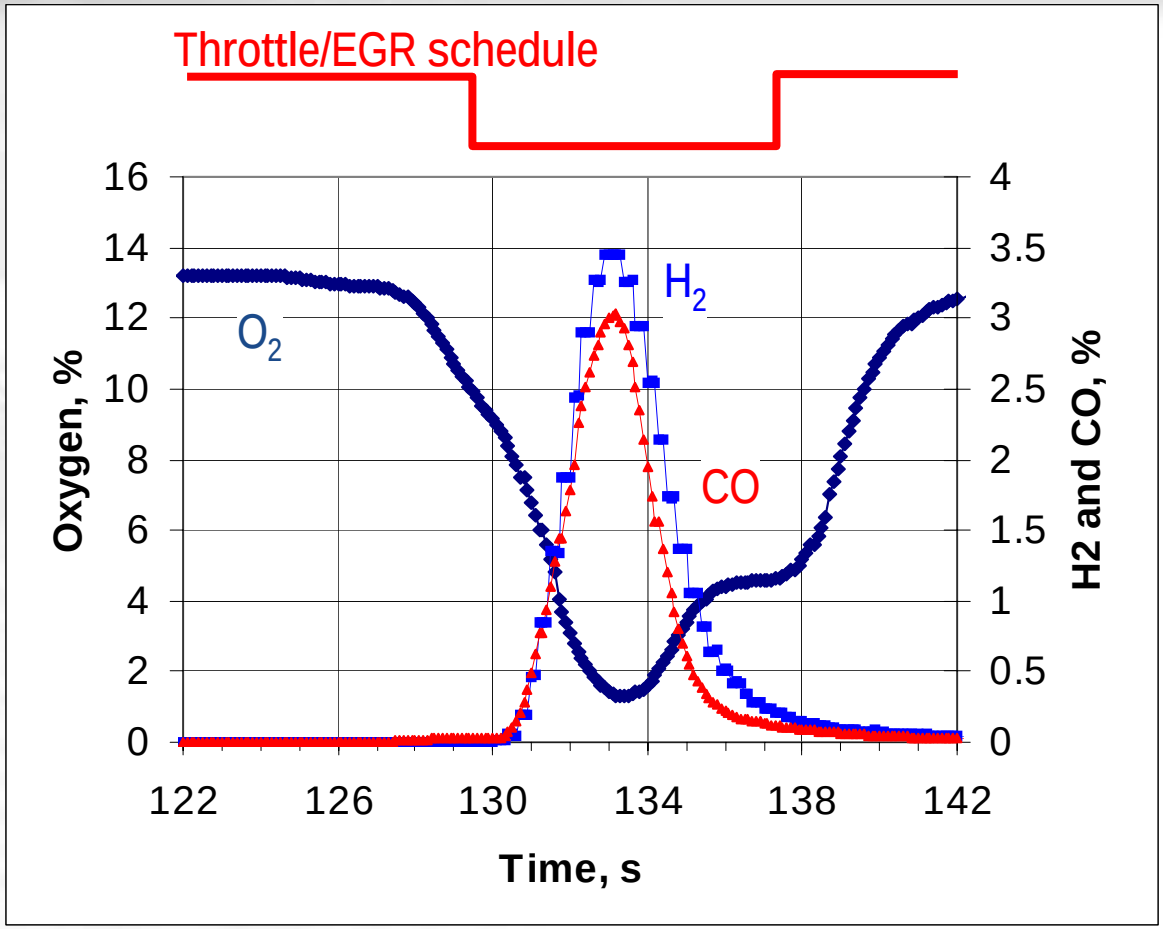
- LNT heat up and desulfation
- Thermal management during PM filter regeneration

Technology for fuel injection integrated into the fuel processor package

- Improved low temperature performance
- Use of “off-the-shelf” injector components

Operational Description of XFP



Test configuration

- 7 liter engine
- Gas analysis downstream of the XFP

Cycle details

- Engine throttled to give exhaust with 5% O_2 during regeneration cycle
- Rich period produces ~3% H_2 and CO
  - 0.4 to 4% H_2 and CO
  - H_2/CO ratio ~ 1
  - Rich pulse length can vary from <1s to many seconds

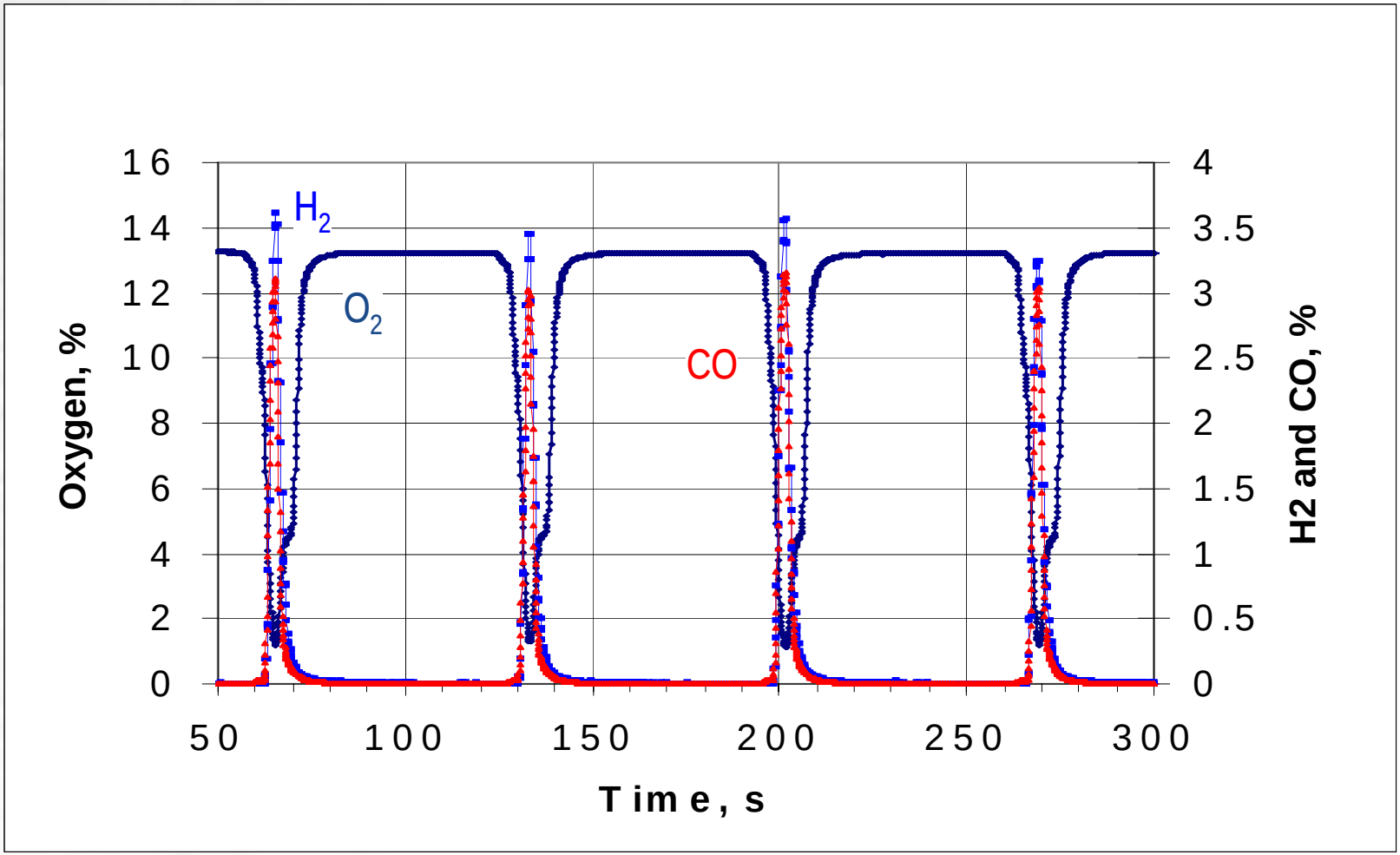
Note: Engine management only required to to lower exhaust O_2 to ~5-7%.

➔Minimizes impact on engine operation

Lean-Rich NOx Adsorber Cycle

Typical engine cycle

- 60 s lean with 3 second rich regeneration



XFP Fuel Efficiency--Discussion

NOx trap (LNT) regeneration requires two conditions to be met

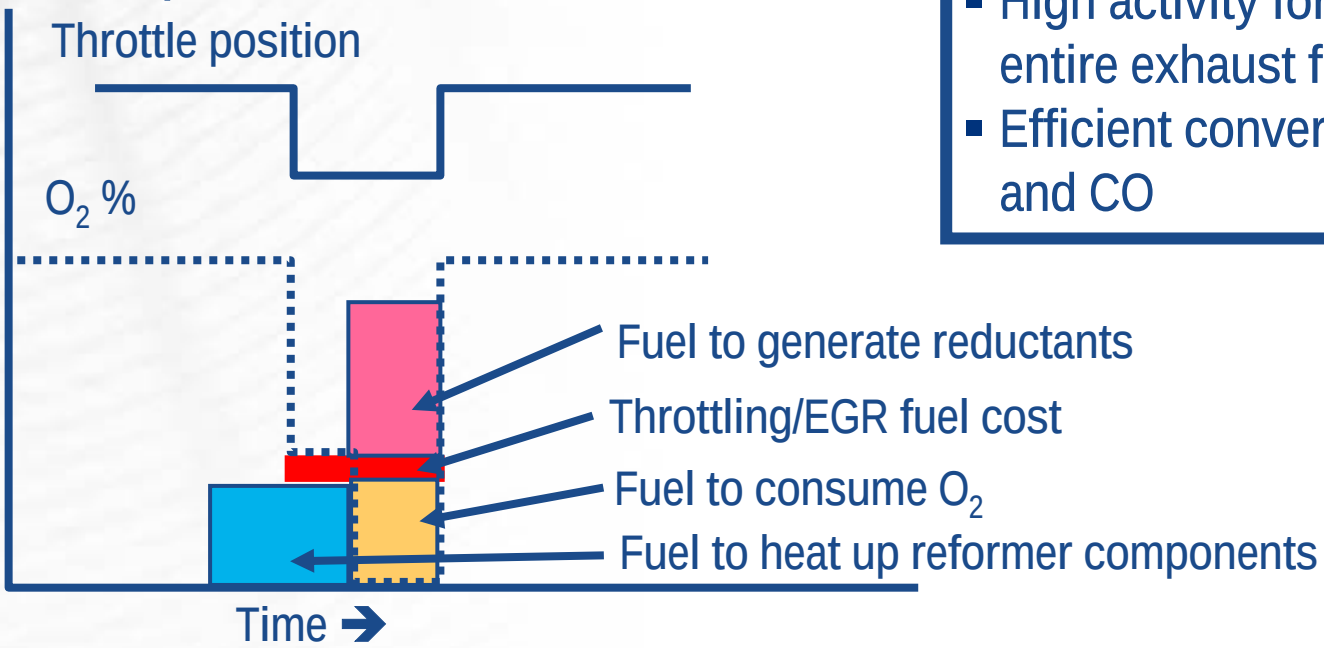
1. O_2 in exhaust must be reduced to zero
2. Reductant must be supplied to reduce stored NOx and regenerate the LNT

- Sources of fuel usage
  - Consume O_2 in the exhaust
  - Reductant to regenerate the NOx trap

XFP design is optimized to achieve

- Very low fuel requirement to heat up the fuel processor components
- High activity for combustion of O_2 in entire exhaust flow
- Efficient conversion of fuel into H_2 and CO

XFP Operation



5 liter engine test

- Older XFP-1 design
  - XFP unit oversized for this engine

5 liter engine
5 liter NOx trap
Test at steady state condition

Speed	Load	XFP inlet temperature	Engine out NOx	Lean trapping time	NOx conversion	Fuel penalty
rpm	Nm	°C	ppm	s	%	%
1600	170	354	130	120	93	4.4
				180	95	3
1600	326	458	380	120	73	2.5
				120	85	3

8 liter engine test

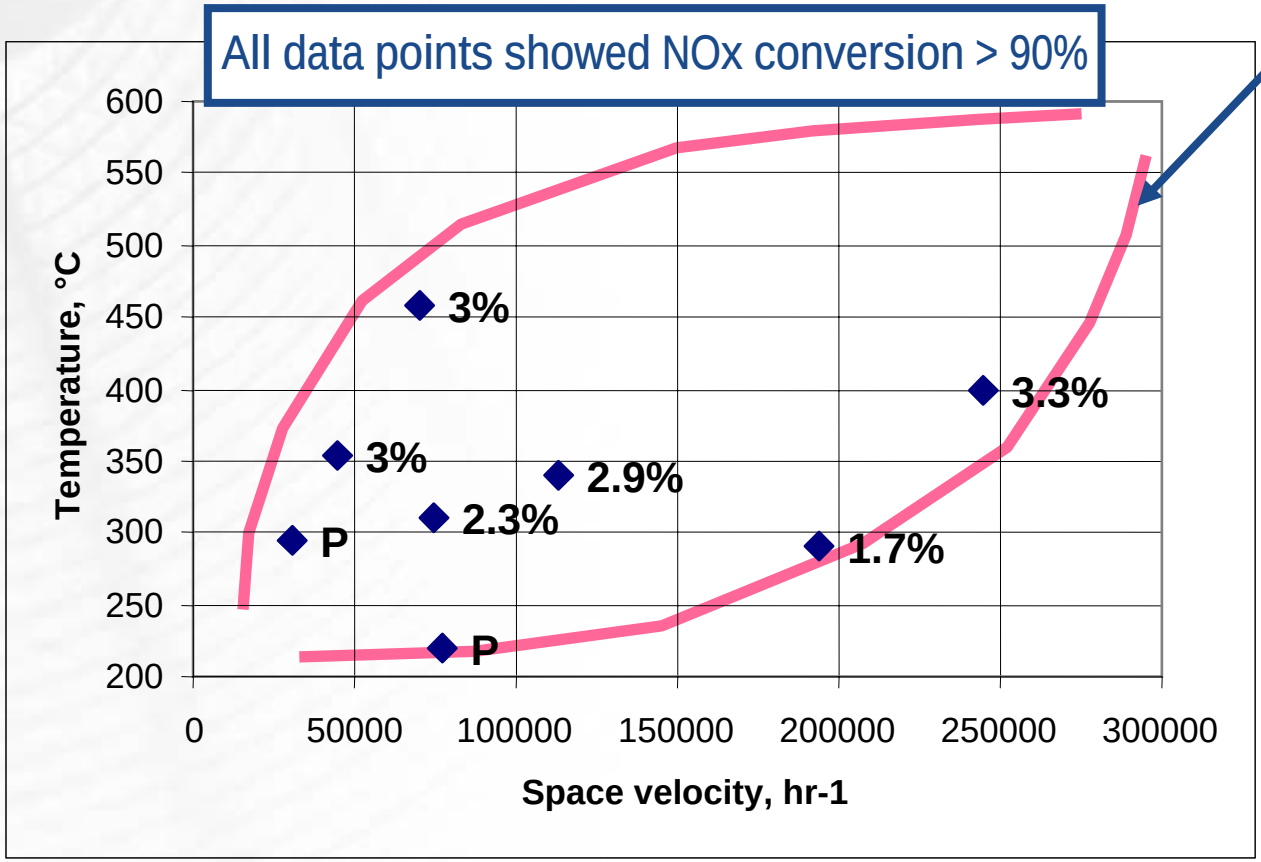
- XFP-1.1 design
  - Improved design with reduced fuel consumption
  - XFP unit sized to this engine

8 liter engine
14 liter NOx trap
Test at steady state condition

Speed	Load	XFP inlet temperature	Engine out NOx	Lean trapping time	NOx conversion	Fuel penalty
rpm	Nm	°C	ppm	s	%	%
1200	380	310	190	60	95	5.4
				120	98	3.2
				180	97	2.3
1200	770	340	430	30	98	4.9
				60	93	2.9
				120	52	1.6

XFP Operating Window

- Desired operating window compared to test points
  - Fuel penalty shown for each test point
  - "P" indicates XFP test only (without NOx trap)



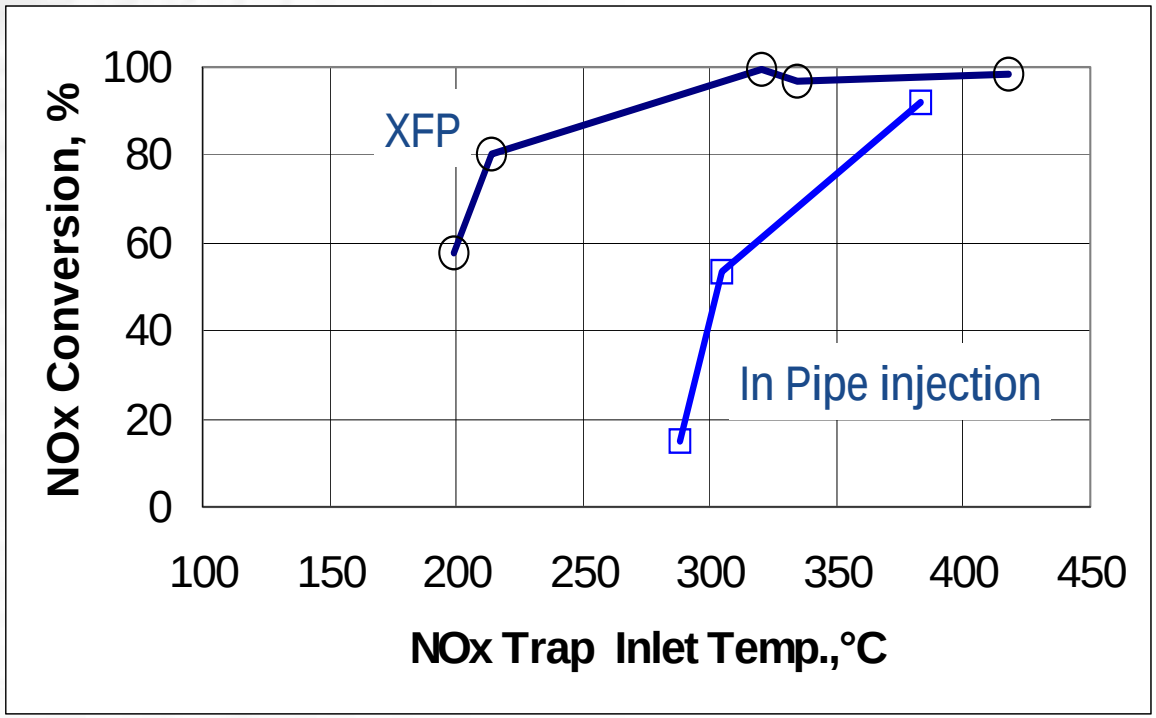
Required operating window still being defined

Operation of LNT at Low Temperature

- H_2+CO reductants give good NOx trap capacity at low temperature

Comments

- Rig data shows H_2+CO will regenerate LNT down to 150°C
- This demonstration was limited by low temperature operation of XFP
- Cycle optimization should allow improved NOx conversion at low temperatures



- 8 liter engine
- 60s lean cycle

Note:

- Exhaust temperature limit of XFP is currently 220°C
- These data obtained using transient engine operation

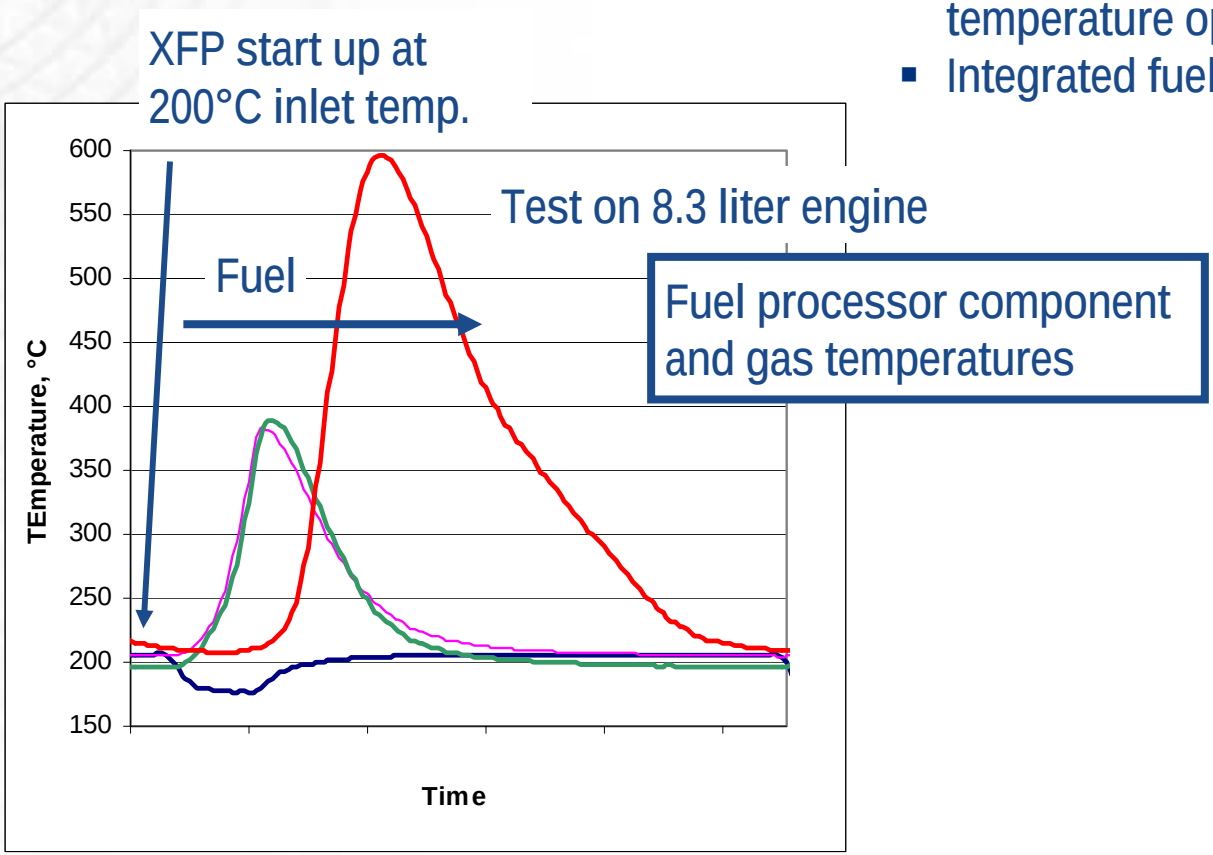
Low Temperature Operation of XFP

Issues

- Fuel injection, mixing and vaporization
- Low temperature light off
- Quick rise to reforming operation

Current status

- XFP can operate with exhaust temperatures down to 220°C
- Development systems show lower temperature operation
- Integrated fuel injection and mixing

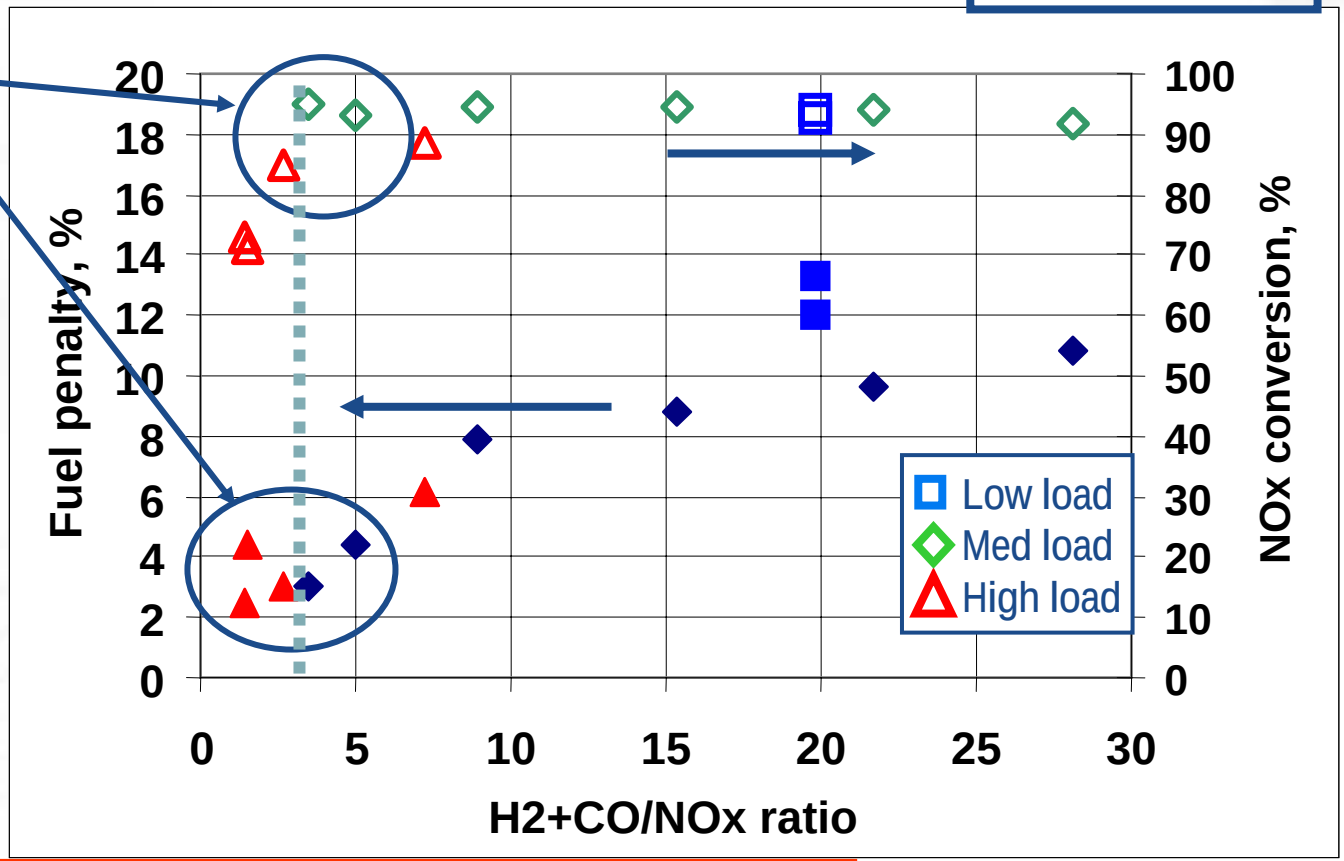


Efficient Use of Reductant

- Reductant to NOx ratio varied by changing “rich” cycle conditions
- Reductant per cycle calculated from measured XFP fuel flow (model)

- 5 liter engine
- 5 liter NOx trap

Region of interest
- Low fuel penalty
- High NOx conversion

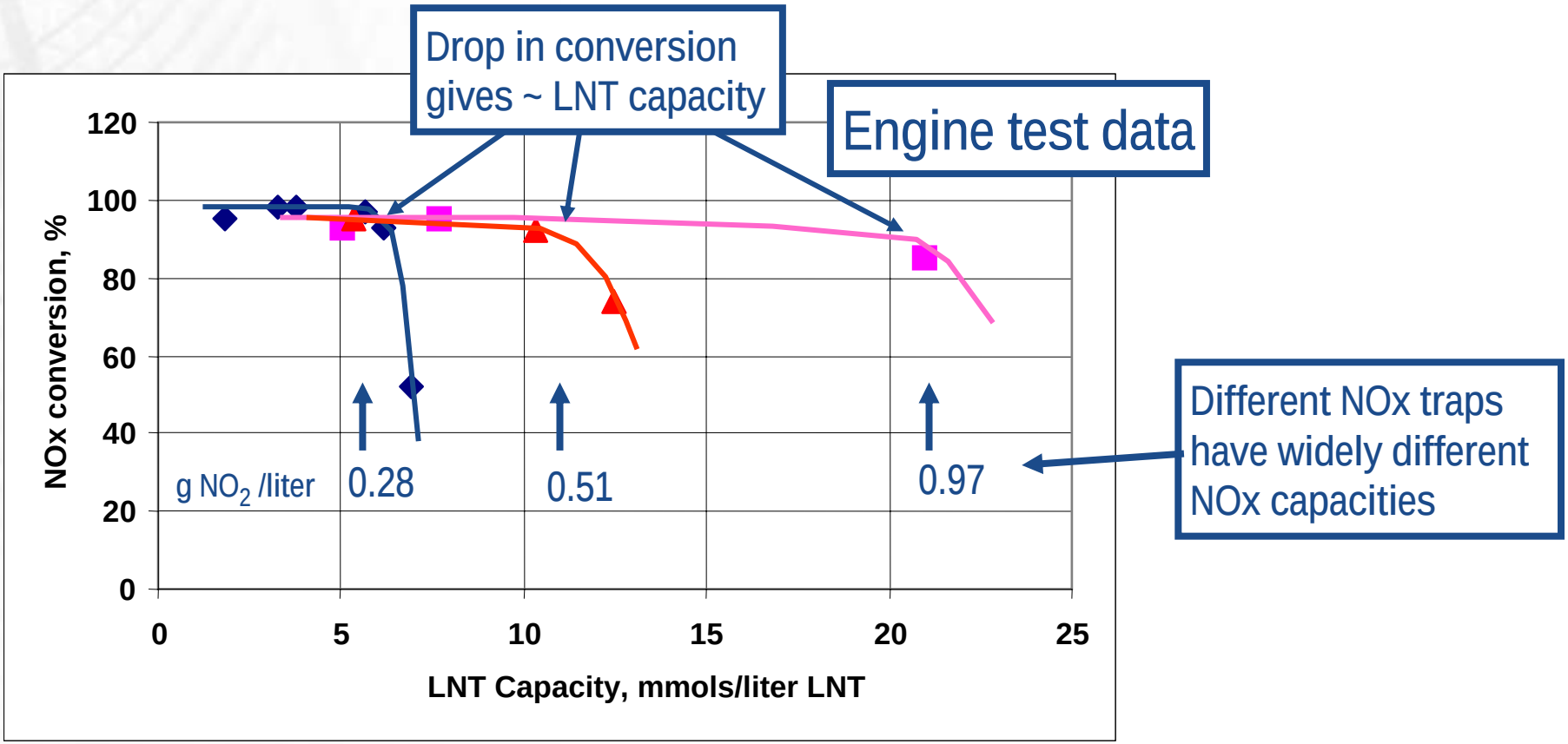


➔ Effective NOx trap can give high NOx conversions with $(CO+H_2)/NOx$ ratios ≥3

NOx Trap Capacity

- High NOx trap capacity demonstrated in engine tests with XFP
  - Cyclic XFP-NOx trap operation at steady state engine operation
  - Vary lean trapping time and rich regeneration time ➔ varies NOx loading on LNT

➔ Very effective LNT regeneration with reactive reductant (H_2+ CO)



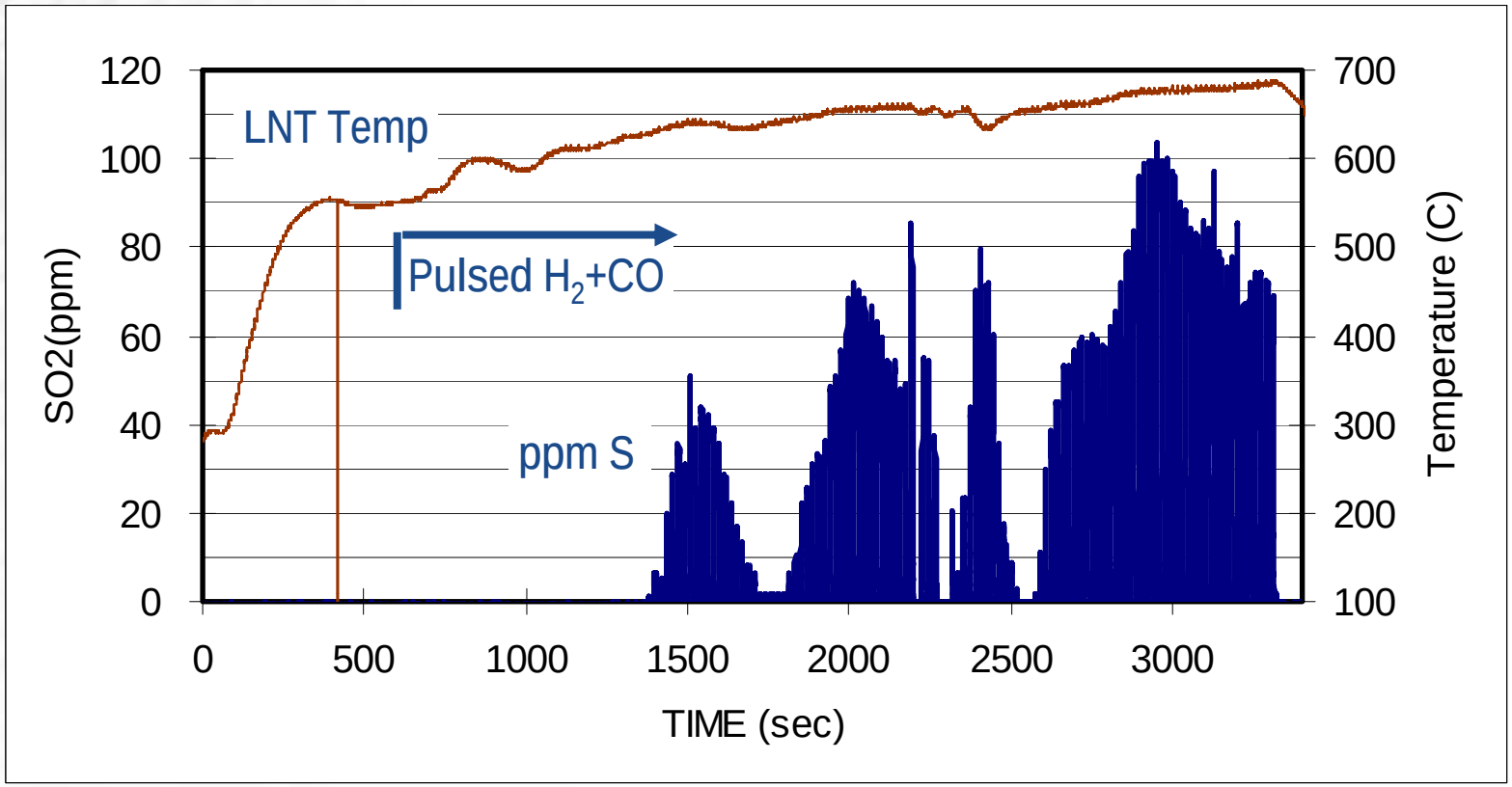
LNT Desulfation Using the XFP

- Strategy
  - Use lean fuel combustion in XFP to raise exhaust temperature into downstream LNT
  - Uniformly heat LNT to desulfation temperature
    - Control can be model based or can use measured exhaust temperature
  - Operate XFP in rich mode to produced continuous or pulsed reductant in the exhaust (H_2+CO) at levels from 0.5% to 3%
    - Rich mode operation uses throttle or EGR to reduce O_2 level to 5-6%

Desulfation: XFP

8 liter engine with 17 liter NOx trap

- XFP provides good LNT temperature control
- XFP provided rich regeneration conditions: ~ 2% H_2+CO
- Desulfation starts at 620°C
- S desorption occurs over a wide temperature range



Summary

- XFP fuel processing system combined with NOx traps demonstrated on 5 to 14 liter diesel engines
  - Engine management limited to reducing exhaust O_2 to ~5% during rich cycle
  - NOx conversion > 90% achieved
  - Lean cycle times typically 60 to 180s
  - Fuel cost in the range of 2 to 3% over most engine conditions
  - XFP operation at exhaust temperatures as low as 220°C
  - Demonstrated regeneration of LNT at exhaust temperatures at low as 200°C
  - Exhaust temperature thermal management
    - LNT desulfation
    - PM filter active regeneration

Status

Work in progress

- Transient engine testing: 4Q2004
- On engine durability testing: 4Q2004
- Engine test of 3ed generation fuel processor design: 1Q05
- On vehicle demonstration: 2Q or 3Q2005

Product improvement directions

- Improved low temperature performance
  - Better coverage of test cycles that emphasize low speed urban conditions
- Shorter regeneration cycle time
  - Easier integration with transient control
- Develop improved transient control strategies
- Durability testing
  - Long term rig testing
  - On-engine testing of components
  - Contaminants testing

Thank you

Contracts

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